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First Light of the CHARIS High-Contrast Integral-Field Spectrograph

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ABSTRACT

One of the leading direct Imaging techniques, particularly in ground-based imaging, uses a coronagraphic system and integral field spectrograph (IFS). The Coronagraphic High Angular Resolution Imaging Spectrograph (CHARIS) is an IFS that has been built for the Subaru telescope. CHARIS has been delivered to the observatory and now sits behind the Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system. CHARIS has 'high' and 'low' resolution operating modes. The high-resolution mode is used to characterize targets in J, H, and K bands at R70. The low-resolution prism is meant for discovery and spans J+H+K bands (1.15-2.37 microns) with a spectral resolution of R18. This discovery mode has already proven better than 15-sigma detections of HR8799c,d,e when combining ADI+SDI. Using SDI alone, planets c and d have been detected in a single 24 second image. The CHARIS team is optimizing instrument performance and refining ADI+SDI recombination to maximize our contrast detection limit. In addition to the new observing modes, CHARIS has demonstrated a design with high robustness to spectral crosstalk. CHARIS has completed commissioning and is open for science observations.

Keywords: Extreme Adaptive Optics, High Contrast Imaging, Integral Field Spectrograph, Exoplanets

1. INTRODUCTION

The Coronagraphic High Contrast Imaging Spectrograph (CHARIS) first light observations were in July 2016, and begin it's science observations in February 2017. CHARIS is an integral field spectrograph (IFS) with two dispersion modes spanning five filters.

Shown in Fig. 1(a), the ND3 and broadband filters are used in the R20 low-resoluiton mode and the J, H, K filters are used with the R70 high resolution prism. Commissioning tasks for CHARIS+SCExAO, shown together in Fig. 1(b), were designed to test functionality and develop observing procedures using these modes. Automated data cube reduction, extended object imaging, astrometry, point source detection at large and small angular separations, and disk detection capabilities are highlighted in this paper.

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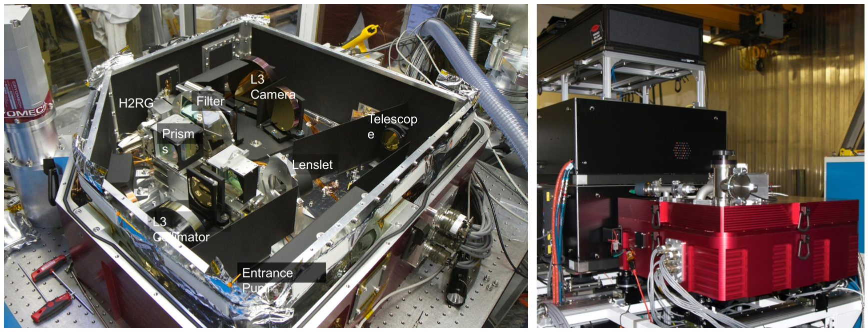


(a) Hilo Final Assembly (b) CHARIS+SCExAO

Figure 1. CHARIS after final assembly in Hilo and installation behind SCExAO at the Subaru Telescope.

2. FIRST-LIGHT AND COMMISSIONING PERFORMANCE

An example of raw IFS data on-sky is shown in Fig. 2. The core of the star is occulted by a hard-edged Lyot coronagraph, which is currently the best broadband coronagraph option available in SCExAO for the CHARIS low-resolution mode (in H-band a vector vortex coronagraph is available). The four streaks are artifical incoherent speckles applied to photometrically calibrate the image and find the centroid of the central star.[1] In the extracted data cubes these are resolved as discrete PSFs, as can be seen in Fig. 6. Zooming in on individual low-resolution (1.15-2.37 μm) spectra in Fig. 2, we can clearly see the two atmospheric absorption lines between J-H and H-K bands.

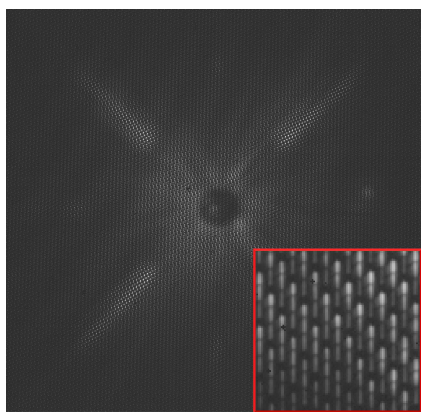
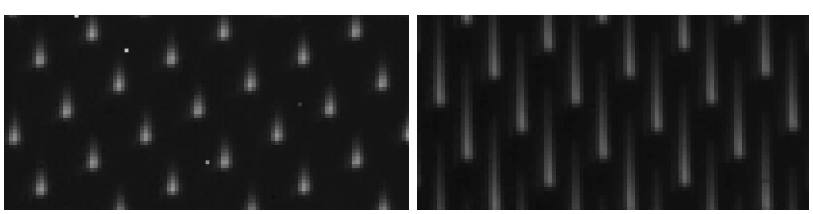


Figure 2. Example of a raw image in broadband mode. Zooming in on the spectra shows atmospheric absorption lines.

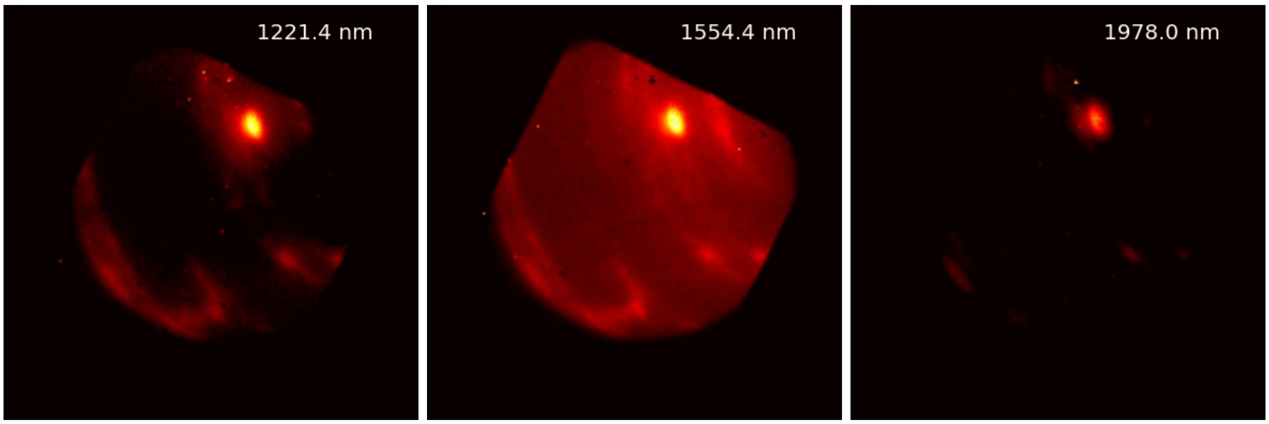
Zooming in on individual spectra in the dispersed thermal background for low-resolution and high-resolution K-band modes are shown in Fig. 3, highlighting the dramatic difference in these modes. Thermal backgrounds are only taken once per night of observing, and are integrated into the data cube reduction generated to convert the raw IFS ramps into science-grade data cubes.



(a) Low-resolution thermal (b) K-band thermal

Figure 3. Zoom in of thermal background in (a) low-resolution and (b) high-resolution K-band modes.

In Fig. 4 we feature a few slices of the data cube from a single 60 second exposure taken of Neptune during commissioning. The evolution of it's structure as a function of wavelength are indicative of composition and cloud structure, something which has been demonstrated at higher spectral resolution in J and H bands in Gibbard et al.[2]

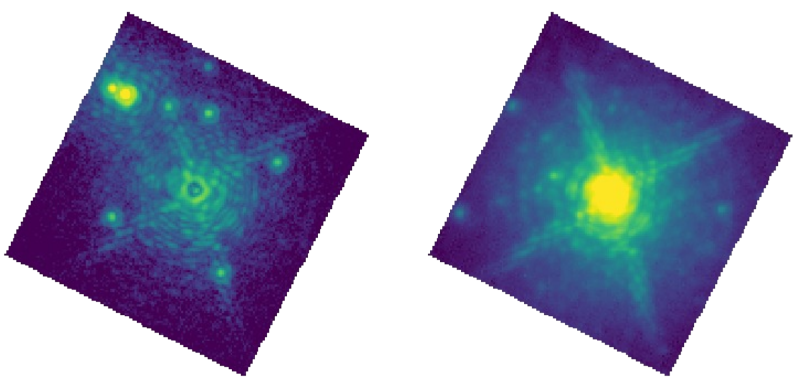


(a) (b) (c)

Figure 4. Three slices of a Neptune data cube as imaged in the CHARIS low-resolution mode.

2.1 Astrometry

As part of commissioning, CHARIS has been mapping distortion and astrometric corrections by looking at multi-star systems. Distortion was principally being measured by observing binary systems through transit, allowing the binary image to rotate over a large angle on the detector. In addition to binary systems, the two principal astrometric calibrators for CHARIS have been Trapezium and M5, shown in Fig. 5. We have identified the region of M5 in Hubble data, and find good agreement between the star field observed by CHARIS. Trapezium is a quad-star system, and we typically observe with the brightest star occulted by the coronagraph to get better signal on the other three stars. With only four stars in the system, we can observe Trapezium with the DM quilting turned on without causing PSF confusion. This allows us to find the centroid the brightest star and calibrate the satellite spots to the sky as a function of wavelength. In addition to Hubble data, Trapezium and M5 are common astrometric calibrators for GPI,[3] allowing us to cross-calibrate the two instruments in the future.

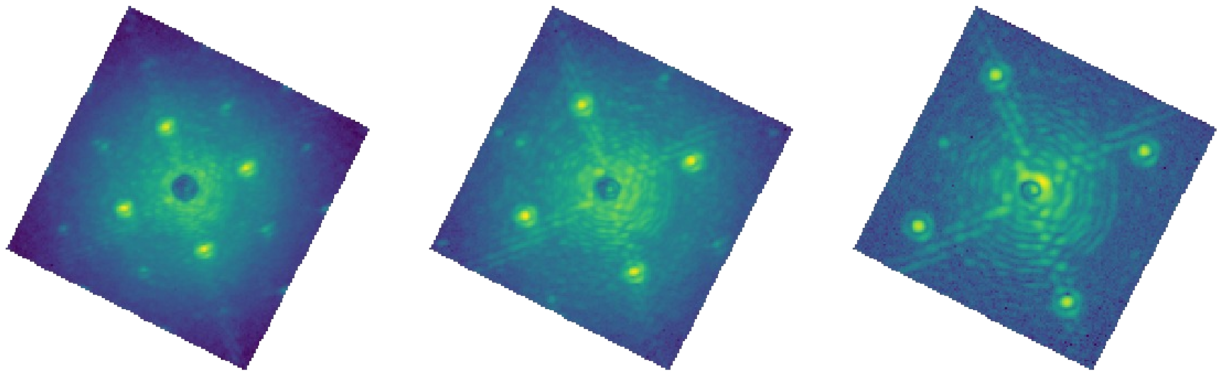


(a) Trapezium (b) M5

Figure 5. Images of our two principal astrometric calibrators for CHARIS, M5 and Trapezium.

2.2 Point Sources

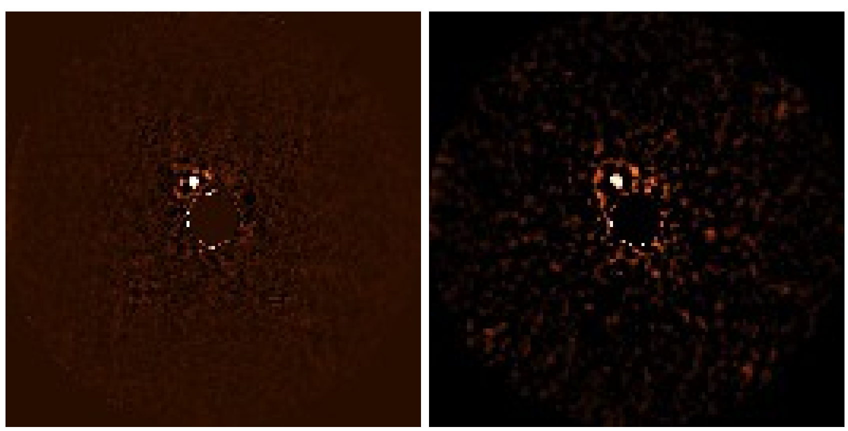
The principal science case for CHARIS is point source detection and characterization. Here we present a few cases that demonstrate high-resolution and low-resolution imaging modes with targets at varying brightness at large and small angular separations. The low-resolution is the workhorse mode of the instrument so we focus on that, but also show an example of K-band high-resolution imaging. A few slices from a cube of the brown



(a) 1200 nm (b) 1630 nm (c) 2213 nm

Figure 6. Three slices from a data cube of HD1160 imaged in the CHARIS low-resolution mode.

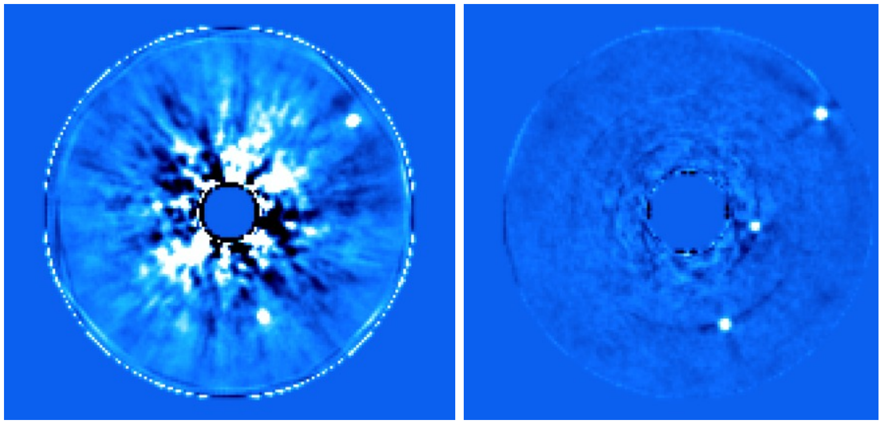
dwarf HD1160 are shown in Fig. 6. HD1160b is quite bright and at large angular separation, so the slices of the data cube are unprocessed. Note the scaling of the artificial speckles in the image as a function of wavelength. We show a high-resolution K-band image of a bright target with low angular separation in Fig. 7. The target is



(a) Mean Cube (b) K-band Slice

Figure 7. Mean of data cube for a 0.2" separation candidate substellar companion imaged in the CHARIS low-resolution mode with post-processing by Maxime Rizzo. (b) A single K-band slice of from the same data set.

quite bright, and at a ~ 0.2" angular separation. The slices in Fig. 7 have a cursory application of angular and spectral differential imaging applied, improving the signal to noise ration (SNR) of the detection. Finally, we show CHARIS data of HR8799 in Fig. 8. The result in Fig. 8(a) uses angular differential imaging (ADI) only. The image in Fig. 8(b) applies both ADI and spectral differential imaging (SDI). There is a clear and impressive improvement in the SNR of the image, with SNR=50, 35, and 15 on HR8799c,d,e respectively. HR8799b is not within the CHARIS field of view.

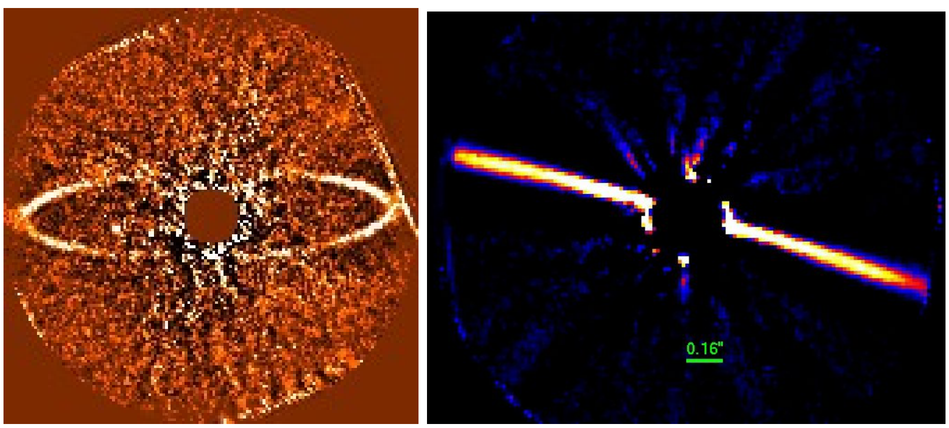


(a) ADI only (b) SDI+ADI

Figure 8. HR8799cde as imaged in the CHARIS low-resolution mode, with variations of ADI and SDI performed by Tim Brandt.

2.3 Extended Objects

Disk science is within the scope of CHARIS science. CHARIS does not currently have a polarization differential imaging (PDI) mode (though one is planned in the future) so we demonstrate the utility of ADI+SDI in detecting disks. Currently, we are still working on getting good signal from face-on disks with few features. However, we



(a) HR4796A (b) HD32297

Figure 9. (a) ADI+SDI processing of HR4796A by Maxime Rizzo. (b) ADI processing of HD 32297 by Thayne Currie, revealing its edge-on debris disk beyond 0.16".

demonstrate good success in extracting HR4796A in Fig. 9(a) despite it's low elevation. A nice image of HD32297 is also shown in Fig. 9(b). The stable PSF provided by SCExAO is key to getting good disk results.

3. DATA CUBE REDUCTION

The standard science grade reduction is a χ-squared reduction technique, and is described in greater detail in Brandt et al.[4] CHARIS is equipped locally with a lower fidelity version of the data reduction pipeline that acts as a watchdog that automatically reduces exposures taken through the telescope control system. The images are identified as being calibration or science data. If it is calibration data, the watchdog automatically generates a new calibration solution for the IFS A snapshot of the autoreducer is shown in Fig. 10. In addition to producing quick look data cubes, the image centroid is found automatically and region photometry is computed to help the observer refine their exposure times, which can vary significantly as a function of seeing and imaging mode.

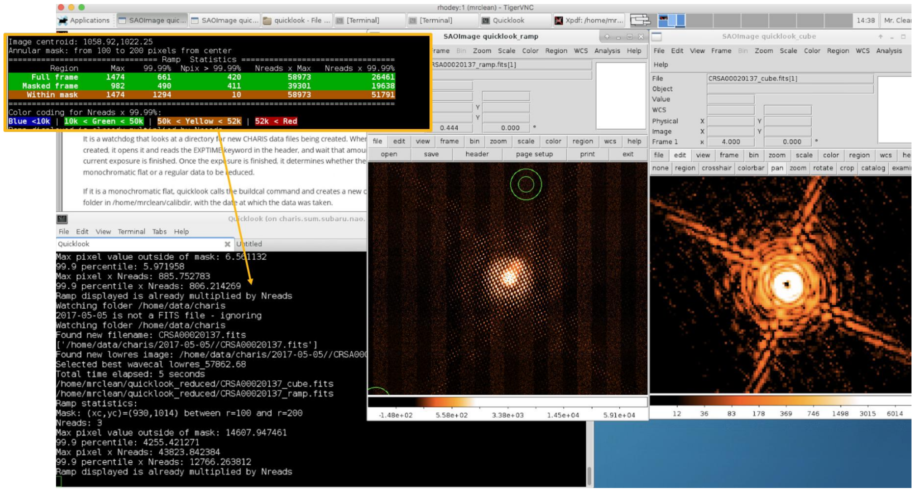


Figure 10. Snapshot of the cube reduction and photometry watchdog on-board the CHARIS computer.

4. SUMMARY

CHARIS completed commissioning and was accepted by the observatory in May 2017. The instrument is now running with SCExAO for science operations. CHARIS+SCExAO operating modes and calibration procedures were refined through commissioning for disk and point source observations. CHARIS is producing very good results on known point source targets and is continuing to develop its disk imaging capabilities to include a PDI mode. CHARIS astrometric corrections are compared to both Hubble data and can be cross-calibrated with GPI data thanks to a common set of calibration targets. The team works closely with the SEEDS community, and are making discovery and characterization follow up visits for disks and companions.

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